Introduction to the OpenGL Shading Language (GLSL)

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The Basic Computer Graphics Pipeline, OpenGL-style

Model Transform → View Transform → Per-vertex Lighting → Projection Transform → Rasterization

MC = Model Vertex Coordinates
WC = World Vertex Coordinates
EC = Eye Vertex Coordinates

The Basic Computer Graphics Pipeline, Shader-style

Vertex Shader

gl_Vertex, gl_Normal, gl_Color

Per-vertex in variables

Uniform Variables

MC → WC → EC → MC

Fragment Shader

gl_Position, Per-vertex out variables

Rasterization

Fragment Processing, Texturing, Per-fragment Lighting

gl_FragColor

Per-fragment in variables

Uniform Variables

Framebuffer

The Basic Computer Graphics Pipeline, Shader-style

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MC = Model Vertex Coordinates
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GLSL Variable Types

attribute
These are per-vertex in variables. They are assigned per-vertex and passed into the vertex shader, usually with the intent to interpolate them through the rasterizer.

uniform
These are "global" values, assigned and left alone for a group of primitives. They are read-only accessible from all of your shaders. They cannot be written to from a shader.

out / in
These are passed from one shader stage to the next shader stage. In our case, out variables come from the vertex shader, are interpolated in the rasterizer, and go in to the fragment shader. Attribute variables are in variables to the vertex shader.

GLSL Shaders Are Like C With Extensions for Graphics:

- Types include int, ivec2, ivec3, ivec4
- Types include float, vec2, vec3, vec4
- Types include mat2, mat3, mat4
- Types include bool, bvec2, bvec3, bvec4
- Types include sampler to access textures
- Vector components are accessed with [index], .rgba, .xyzw, or.stpq
- You can ask for parallel SIMD operations (doesn't necessarily do it in hardware):
  \[ \text{vec4 a, b, c; } \]
  \[ a = b + c; \]
- Vector components can be "swizzled" ( c1.rgba = c2.abgr )
- Type qualifiers: const, attribute, uniform, in, out
- Variables can have "layout qualifiers" (more on this later)
- The discard operator is used in fragment shaders to get rid of the current fragment

The discard Operator Halts Production of the Current Fragment

```cpp
if ( random_number < 0.5 )
    discard;
```

GLSL Shaders Are Missing Some C-isms:

- No type casts -- use constructors instead: int i = int( x );
- Only some amount of automatic promotion (don’t rely on it)
- No pointers
- No strings
- No enums
- Can only use 1-D arrays (no bounds checking)

**Warning:** integer division is still integer division !

```cpp
float f = float( 2 / 4 );  // still gives 0. like C, C++, Python, Java
```
A GLSL Vertex Shader Replaces These Operations:

- Vertex transformations
- Normal transformations
- Normal unitization (normalization)
- Computing per-vertex lighting
- Taking per-vertex texture coordinates (s,t) and passing them through the rasterizer to the fragment shader

Built-in Vertex Shader Variables You Will Use a Lot:

`vec4 gl_Vertex`
`vec3 gl_Normal`
`vec4 gl_Color`
`vec4 gl_MultiTexCoord0`
`mat4 gl_ModelViewMatrix`
`mat4 gl_ProjectionMatrix`
`mat4 gl_ModelViewProjectionMatrix`
`mat4 gl_NormalMatrix` (this is the transpose of the inverse of the MV matrix)
`vec4 gl_Position`

Note: while this all still works, OpenGL now prefers that you pass in all the above variables (except `gl_Position`) as user-defined attribute variables. We’ll talk about this later. For now, we are going to use the easiest way possible.

A GLSL Fragment Shader Replaces These Operations:

- Color computation
- Texturing
- Handling of per-fragment lighting
- Color blending
- Discarding fragments

Built-in Fragment Shader Variables You Will Use a Lot:

`vec4 gl_FragColor`

Note: while this all still works, OpenGL now prefers that you pass in all the above variables (except `gl_Position`) as user-defined attribute variables. We’ll talk about this later. For now, we are going to use the easiest way possible.
My Own Variable Naming Convention

With 7 different places that GLSL variables can be written from, I decided to adopt a naming convention to help me recognize what program-defined variables came from what sources:

<table>
<thead>
<tr>
<th>Beginning letter(s)</th>
<th>Means that the variable ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Is a per-vertex attribute from the application</td>
</tr>
<tr>
<td>u</td>
<td>Is a uniform variable from the application</td>
</tr>
<tr>
<td>v</td>
<td>Came from the vertex shader</td>
</tr>
<tr>
<td>tc</td>
<td>Came from the tessellation control shader</td>
</tr>
<tr>
<td>te</td>
<td>Came from the tessellation evaluation shader</td>
</tr>
<tr>
<td>g</td>
<td>Came from the geometry shader</td>
</tr>
<tr>
<td>f</td>
<td>Came from the fragment shader</td>
</tr>
</tbody>
</table>

This isn’t part of “official” OpenGL – it is my way of handling the confusion.

The Minimal Vertex and Fragment Shader

```glsl
// version 330 compatibility
void main() {
    gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
    // This makes sure that each vertex gets transformed
}
```

```glsl
void main() {
    gl_FragColor = vec4( .5, 1., 0., 1. );
    // This assigns a fixed color and alpha to each fragment drawn
}
```

A Reminder of what a Rasterizer does

There is a piece of hardware called the Rasterizer. Its job is to interpolate a line or polygon, defined by vertices, into a collection of fragments. Think of it as filling in squares on graph paper.

A fragment is a “pixel-to-be”. In computer graphics, “pixel” is defined as having its full RGBA already computed. A fragment does not yet but all of the information needed to compute the RGBA is there.

A fragment is turned into a pixel by the fragment processing operation.

Rasterizers interpolate built-in variables, such as the (x,y) position where the pixel will live and the pixel’s z-coordinate. They can also interpolate user-defined variables as well.

A Little More Interesting

```glsl
// version 330 compatibility
out vec3 vColor;
void main() {
    vec4 pos = gl_Vertex;
    vColor = pos.xyz; // set rgb from xyz!
    gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

```glsl
in vec3 vColor;
void main() {
    gl_FragColor = vec4( vColor, 1. );
    // Not terribly useful ...
}
```
Setting rgb From xyz, I

vColor = gl_Vertex.xyz;

What's Changed About This?

Vertex shader:

```glsl
#version 330 compatibility
out vec3 vColor;

void main()
{
  vec4 pos = gl_ModelViewMatrix * gl_Vertex;
  vColor = pos.xyz; // set rgb from xyz!
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Fragment shader:

```glsl
#version 330 compatibility
in vec3 vColor;

void main()
{
  gl_FragColor = vec4( vColor, 1. );
}
```

Setting rgb From xyz, II

vColor = ( gl_ModelViewMatrix * gl_Vertex ).xyz;

What's Different About This?

Set the color from the **pre-transformed (MC)** xyz:

```glsl
#version 330 compatibility
out vec3 vColor;

void main()
{
  vec4 pos = gl_Vertex;
  vColor = pos.xyz; // set rgb from xyz!
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Set the color from the **post-transformed (WC/EC)** xyz:

```glsl
#version 330 compatibility
out vec3 vColor;

void main()
{
  vec4 pos = gl_ModelViewMatrix * gl_Vertex;
  vColor = pos.xyz; // set rgb from xyz!
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```
Computer Graphics

Setting rgb From xyz

\[ vColor = \text{gl\_Vertex}.xyz; \]

\[ vColor = (\text{gl\_ModelViewMatrix} \times \text{gl\_Vertex}).xyz; \]

Vertex shader:

```
#version 330 compatibility

out vec2 vST; // texture coords
out vec3 vN; // normal vector
out vec3 vL; // vector from point to light
out vec3 vE; // vector from point to eye

const vec3 LIGHTPOSITION = vec3(5., 5., 0.);

void main(
) {
  vec4 ECposition = gl_ModelViewMatrix * gl_Vertex;
  vN = normalize(gl_NormalMatrix * gl_Normal); // normal vector
  vL = LIGHTPOSITION - ECposition.xyz; // vector from the point to the light position
  vE = vec3(0., 0., 0.) - ECposition.xyz; // vector from the point to the eye position
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Fragment shader:

```
#version 330 compatibility

uniform float uKa, uKd, uKs; // coefficients of each type of lighting
uniform vec3 uColor; // object color
uniform vec3 uSpecularColor; // light color
uniform float uShininess; // specular exponent
in vec2 vST; // texture cords
in vec3 vN; // normal vector
in vec3 vL; // vector from point to light
in vec3 vE; // vector from point to eye

void main(
) {
  vec3 Normal = normalize(vN);
  vec3 Light = normalize(vL);
  vec3 Eye = normalize(vE);
  vec3 ambient = uKa * uColor;
  float d = max(dot(Normal,Light), 0.); // only do diffuse if the light can see the point
  vec3 diffuse = uKd * d * uColor;
  float s = 0.;
  if(dot(Normal,Light) > 0.) { // only do specular if the light can see the point
    vec3 refl = normalize(reflect(-Light,Normal));
    float a = pow(dot(Eye,refl),uShininess);
    vec3 specular = uKs * a * uSpecularColor;
    gl_FragColor = vec4(ambient + diffuse + specular, 1.);
  }
}
```

Per-fragment Lighting

Ambient

Diffuse

Specular

All together now!
Within the fragment shader, find out if the current fragment is within a particular rectangle:

```glsl```
vec3 myColor = uColor;
if( uS0-uSize/2. <= vST.s && vST.s <= uS0+uSize/2. && uT0-uSize/2. <= vST.t && vST.t <= uT0+uSize/2. ) {
    myColor = vec3( 1., 0., 0. );
}
vec3 ambient = uKa * myColor;
```glsl```

```
Here's the cool part: It doesn't matter (up to the limits of 32-bit floating-point precision) how far you zoom in. You still get an exact crisp edge. This is an advantage of procedural (equation-based) textures, as opposed to texel-based textures.
```
Setting Up Texturing in Your C/C++ Program

This is the hardware Texture Unit Number. It can be 0-15 (and often a lot higher depending on the graphics card).

```c
// globals:
unsigned char * Texture;
GLuint TexName;
...
// In InitGraphics():
glGenTextures( 1, &TexName );
int nums, numt;Texture = BmpToTexture( "filename.bmp", &nums, &numt );
gBindTexture( GL_TEXTURE_2D, TexName );
gTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_WRAP_S, GL_REPEAT );
gTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_WRAP_T, GL_REPEAT );
gTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_MAG_FILTER, GL_LINEAR );
gTexParameterf( GL_TEXTURE_2D, GL_TEXTURE_MIN_FILTER, GL_LINEAR );
gTexImage2D( GL_TEXTURE_2D, 0, 3, nums, numt, 0, 3, GL_RGB, GL_UNSIGNED_BYTE, Texture );
...
// In Display():
Pattern->Use();
gActiveTexture( GL_TEXTURE5 );  // use texture unit 5
Pattern->SetUniformVariable( "uTexUnit", 5 );  // tell your shader program you are using texture unit 5
<< draw something >>
Pattern->Use( 0 );
```

2D Texturing

Vertex shader:

```c
#version 330 compatibility
out  vec2  vST;

void
main() {
  vST = gl_MultiTexCoord0.st;
  gl_Position = gl_ModelViewProjectionMatrix * gl_Vertex;
}
```

Fragment shader:

```c
#version 330 compatibility
in  vec2  vST;
uniform sampler uTexUnit;

void
main() {
  vec3 newcolor = texture( uTexUnit, vST ).rgb;
  gl_FragColor = vec4( newcolor, 1. );
}
```

Hints on Running Shaders on Your Own System

- You need a graphics system that is OpenGL 2.0 or later. Basically, if you got your graphics system in the last 5 years, you should be OK. If you don’t have access to such a system, use the CGEL. (The most recent OpenGL level there is 4.6)
- Update your graphics drivers to the most recent level!
- If you are on Windows, you must do the GLEW setup. It looks like this in the sample code:
  ```c
  GLenum err = glewInit();
  if( err != GLEW_OK )
    {
      fprintf( stderr, "glewInit Error!
      
      But if( err = GLEW_INITIALIZED_OK !=
      
      else
      fprintf( stderr, "GLEW initialized OK!
      ```
  
  And, this must come after you’ve opened a window. (It is this way in the code, but I’m saying this because I know some of you went in and “simplified” the sample code by deleting everything you didn’t think you needed.)
- You can use the GLSL C++ class you’ve been given only after GLEW has been setup. So, initialize your shader program:
  ```c
  bool valid = Pattern->Create( "pattern.vert", "pattern.frag" );
  after successfully initializing GLEW.
  ```
Declaring the GLSLProgram above the main program (as a global):

GLSLProgram * Pattern;

At the end of InitGraphics(), create the shader program and setup your shaders:

Pattern = new GLSLProgram();
bool valid = Pattern->Create("project.vert", "project.frag");
if (! valid) {
    ...
}

Use the Shader Program in Display():

Pattern->Use();
Pattern->SetUniformVariable( ...  

Draw the object here

Pattern->Use( 0 );  // return to fixed functionality

Tips on drawing the object:

- If you want to key off of s and t coordinates in your shaders, the object had better have s and t coordinates assigned to its vertices – not all do!
- If you want to use surface normals in your shaders, the object had better have surface normals assigned to its vertices – not all do!
- Be sure you explicitly assign all of your uniform variables – no error messages occur if you forget to do this – it just quietly screws up.
- The glutSolidTeapot has been textured in patches, like a quilt – cute, but weird.
- The MjbSphere() function from the texturing project will give you a very good sphere.